



RADC-TR-80-83 Final Technical Report March 1980



LANGUAGE RECOGNITION TEST AND EVALUATION

Texas Instruments, Incorporated

Dr. Gary Leonard



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A collection of 80 reference sounds was generated from 66 design speakers of the seven available languages.

These references were used in a 65-speaker, 7-language evaluation, where 100% correct classification was obtained using a rejection threshold that yielded 68% rejection. A five-language test indicated that 56% rejection provided zero classification errors.

A data processor simulation was implemented that incorporated automatic detection of onset and cessation of speech, along with concurrent aural playout of either the incoming data or operator-selected, prestored data.

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PREFACE

This Final Report describes research on automatic language classification by Texas Instruments Incorporated, Central Research Laboratories, 13500 North Central Expressway, Dallas, Texas, under Contract No. F30602-78-C-0075 for Rome Air Development Center, Griffiss Air Force Base, New York. Mr. Richard S. Vonusa (IRAA) was the RADC Project Engineer. The report covers work performed from February 1978 through August 1979.

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EVALUATION

This report discusses a language recognition algorithm that uses multiphoneme reference sounds in conjunction with a summed log-likelihood decision rule to automatically classify languages.

This effort extended the RADC data base from five to seven different languages.

In experiments using 65 test speakers for the seven languages, tradeoff curves were generated in which high language classification rates were achieved at the expense of a greater number of language rejections.

It was found that it is possible to attain 100 percent correct language classification with a reject rate of 68 percent or 62 percent correct language classification with no rejects.

The results of this program are quite encouraging and this technology may have potential application for monitoring communication channels containing languages of interest.

RICHARD S. VONUSA

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Project Engineer

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SECTION I

Automatic language classification is a challenging speech processing problem. The three classic problem areas, unknown speaker, unknown text, and connected speech, are intrinsic parts of the automatic language classification problem. Fortunately, many seconds of speech data may be used to form a decision. The ideal strategy is to determine key sound sequences (words or phrases, for example) which are highly language specific and then perform limited sequence recognition and classify the language accordingly.

This report documents the results of the fourth in a series of language classification studies conducted at Texas instruments. In the first two studies^{1,2} automatic techniques were developed for selecting key reference sounds, these techniques being independent of the particular languages considered. In the third study³ an interactive approach was taken in the generation of reference sounds, and somewhat improved results were obtained. During this fourth study the number of languages in the data base was increased from five to seven (see Section II) and the interactive approach to reference generation was extended to allow more accuracy in specifying reference sounds and more flexibility in the allowed types of reference sounds. The method of reference generation is described in Section III.

Application was made of a criterion for rejection; i.e., not classifying a speaker when the basis for such a decision is not sufficiently strong. The classification and rejection strategies are described in Section IV.

Section V describes the results of applying these strategies and reference sounds to an independent collection of test speakers. It was found (in a seven-language test) that 100% correct classification was obtained after rejecting 68% of the test speakers. In a five-language test it was found that

100% correct classification was obtained after rejecting only 56% of the test speakers. These results indicate that significant reduction can be made in required manual monitoring of data to determine language by applying these automatic techniques.

Section VI describes a real-time simulation of a data processing system that detects the onset and cessation of speech in the signal and flags the probable occurrence of changes in the particular speaker. In addition, this system allows storage of the digitized data for subsequent playback when specified by an operator; hard copy record of times and durations of speech events of particular importance; and aural monitoring of the incoming signal whenever desired.

SECTION II MULTI-LANGUAGE DATA BASE

A. Pre-Existing Data

Analog speech data recordings from speakers of five languages were provided by RADC. These languages will be denoted L1, L2, L3, L4, and L5. This collection of data comprised speakers recorded in a variety of environments ranging from acoustically treated sound rooms to highly reverberant rooms in a church. One, two, or three 15-minute sessions of speech (read text) were provided from each speaker.

B. Data Collection

During the course of this study, over a period of four months, speech data from speakers of two additional languages were collected. These languages are denoted L7 and L8; L6 is reserved for English. One, two, three, or four 10-minute sessions of speech (text read from a book or magazine) were provided by each speaker. Thirty-one sessions of data were collected from 17 speakers of L7 and thirty-three sessions of data were collected from 14 speakers of L8.

The new data were recorded in the TI Speech Systems Research Laboratory in a Tracoustics, Inc., acoustic enclosure, Model RE-244B, using an Electro-Voice 635A microphone, and recorded on a TEAC 4010 SL analog recorder. The data were recorded on 1/4 inch analog tape at a speed of 7 1/2 ips.

C. Processed Data

Table 1 shows the composition of two subsets of the available data base used for experiments during this study. The first subset contains data from

66 speakers whose data (design data) were used to generate reference sounds and to determine parameters of the decision strategies. The second subset contains data from 65 speakers whose data (test data) were used to estimate the probabilities of rejection and correct decisions. For each speaker in the two subsets, one two-minute segment of data was extracted from the first session donated by that speaker. The source speakers for the test data are distinct from the source speakers for the design data.

Table 1

Compositions of Sets of Design Speakers and Test Speakers

Language	L1	L2	L3	<u>L4</u>	L5	L7	L8	Totals
Number of Design Speakers	10	10	10	10	10	9	7	66
Number of Test Speakers	10	6	10	14	10	8	7	65
Totals	20	16	20	24	20	17	14	131

D. Data Processing

Each segment of analog data was passed through a 5 kHz anti-alias low pass analog filter and then digitized at a 10 kHz sampling rate. The digitized data were then stored on a random access storage disk. All subsequent signal processing is digital in nature. A hardware vector comparator and an array processor were utilized to reduce computation time.

The digital signal was first applied to a digital filter bank simulator to produce 16-filter filter-bank output which matches the filter-bank output described in Appendix A, Reference 5. Then each speaker's long-term average spectrum was determined and used to modify his filter-bank data so that the new long-term average spectrum is the standard long-term average spectrum described in detail in Section IV.C, Reference 3. This spectrum standardizing procedure was shown there to greatly enhance language discrimination.

Then the outputs of the three high-frequency filters are summed to form a substitute for the 14th filter-bank output, and the original outputs of filters 14, 15 and 16 are disregarded. The 14-filter filter-bank output data are then downsampled to 100 samples per second, regressed, amplitude normalized, and quantized to eight equiprobable levels (three bits) just as described in Appendix A, Reference 5. In addition, also as described there, two quantized regression coefficients and a (non-quantized) measure of energy are appended to this preprocessed spectral data vector to form the complete representation of speech every 10 ms.

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SECTION III REFERENCE SELECTION

The steps taken in this study to effect automatic language discrimination were:

- (1) Determine a set of key reference sounds (words or phrases) which are frequently occurring and language specific;
- (2) Process the design data to automatically detect and count recurrences of these sounds to compute parameters of a decision function;
- (3) Process each test speaker's data to detect and count recurrences of each of the key sounds to evaluate its decision function values (one for each possible language); and
- (4) Either reject the speaker, i.e., not make a decision as to language for that speaker, or decide upon the language that yields the best decision function value.

This section describes the interactive procedures applied to accomplish step (1), the selection of key reference sounds.

For each of the seven languages studied, the following procedures were used to determine the sounds that occurred multiple times and were of sufficient length to be detected reliably. The input to the procedures is a file of digitized speech (of two minutes duration) stored on disk. The tool that facilitated this procedure is a computer program (named MONITOR) that allows aural playout of the stored speech data in a flexible manner.

A. Data Transcription and Analysis

Data from six speakers were phonetically transcribed to provide a hardcopy version of these speakers' data. MONITOR provides TTY keyboard control of the data playout to aid this manual transcription. Specifically useful here are two keyboard controls. The first key, when pressed, stops the playout and repeatedly plays back the two seconds of data immediately preceding the time of key depression. This allows assuring that the speech sounds are correctly transcribed before proceeding. The second key provides resumption of data playout when the transcription of the two-second segment is complete.

The transcriptions of each of the six two-minute segments of data were then analyzed manually to determine and list those multiple-phoneme sounds that occurred more than one time. These sounds typically contain 3, 4, or 5 phonemes. The numbers of occurrences of each of these sounds were noted so that the ones that recur most frequently can be processed first.

For each listed sound, a third function of MONITOR was used to isolate representative occurrences of the sound, verify the occurrence by listening to repeated playout of the sound, and then store in a disk file the beginning time and duration of the sound (relative to the beginning of the source speaker's speech segment). Then a fourth MONITOR function was used to produce, for each version of each sound, a line-printer figure showing the 14-filter spectrum, along with the energy profile, the two regression coefficients, and the transitionitivity function.² An example printout is shown in Figure 1.

The next subsection describes the procedure for obtaining a reference pattern to be used in the process of detecting the recurrence of a sound such as the ones isolated as described above.

Sample No. Value *)(00) +)(0+) 100779915622 gipai Sipai Pipe. (0\$)(\$ 16412 (8\$)(\$ 61631 (08)(\$ 2) (26) 2) (28) 2) (28) 2) (28) 2) (22) 2) (22) 2) (22) 2) (22) 2) (22) IIPUI 40101 60001 40001 40001 11)89 14)55 41)68 11)18 '')60t 96901 (')69T 50,01 12 P8981 ..)SRI 10 162 113(" 60001 (+\$) (a 10)64 4 TUPOL Data from Speaker S2 of Language L3 ('s)((6) 38 00001 \$) \{\text{8}}\$\tag{\$\text{7}}\$ 56181 86761 45201 500(8" 96101 + 189 m 1 m 189 + m 18 511 (8" 4678! 7678! 183692 502(2 18482 Seg(2 Seg(2 Seg(2 Seg(2 6610: 16201 "" = O = " ,
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9

Level

Spectrum Legend:

0

Symbol S

Figure I Example of Reference Sound Specification

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B. Generation of a Reference Pattern

The term <u>reference pattern</u> is used in this report to indicate a set of vectors stored in computer memory which represents a key sound and can be used to automatically detect the recurrence of that key sound within an incoming data stream. The first step in defining a reference pattern is to determine the reference points within the sound—those points which can be automatically determined with great reliability using the scanning procedure described in Reference 4, pp.18-21. High reliability can be achieved when reference points are chosen at times of high spectral change. A plot of the transitionitivity function, T, was used as a visual aid in selecting reference points, such selection being made at times of significant peaks in the T function. From two to six points were selected for each sound to be processed. The reference points selected for the sound shown in Figure 1 are indicated there by triangles.

Following the manual selection of reference point times and the TTY input of these times to a reference selection computer program (denoted REFSEL), this program extracted a scanning pattern for each reference point and formatted a recognition pattern for the complete sound. The definitions of scanning pattern and recognition pattern are described in Section II, Reference 4. The format of the recognition patterns extracted during this study is as follows. No extrapolation was done, i.e., no columns were extracted prior to the first reference point, and no columns were extracted following the last reference point of the sound. The number of columns extracted between reference points depends only on the number of samples between reference point times as follows:

# Sample Be tween	# Columns Extracted
Reference Points	(Linear Interpolation)
< 4	2
4-10	3
11-20	į
>20	8

Also described in Section II, Reference 4 are the three processes:

(1) scanning (to determine occurrences of reference points); (2) hypothesizing sequences of reference points; and (3) verifying occurrences of the reference sound. These same processes (which together effect a word recognition system) were carried out within REFSEL with the following two fillets. First, whenever a reference sound has been detected, several processing parameters are displayed on a CRT output device, and processing halts. Second, repeated aural playout is made of those speech data that were detected as being an occurrence of the reference sound.

Three conditions must be satisfied for REFSEL processing to halt indicating a detected reference sound. First, the scanning error valley point value, denoted SE, for each reference point must be smaller than a specified threshold (referred to as SEmax), where this threshold may be different for each reference point in the sound. For the sounds considered in this study this threshold was made equal to the moderately high value SEmax = 400, for each reference point. This value was used to allow consideration of sounds with large spectral variations at the reference point level and is necessitated by the speaker- and text-independent nature of the data.

Second, the sequence error, denoted SQ, that results from the hypothesis of a valid sequence of reference points must be smaller than a specified threshold (referred to as SQmax), which may depend on the particular reference sound. For reference generation, this threshold was set to: SQmax = 300*(NRP-1), where NRP is the number of reference points in the reference sound. This is a very high value for this threshold and allows consideration of all sequences that resemble, even remotely, the input reference sound.

The third condition required is that the recognition error, denoted TE, be smaller than a specified threshold, referred to as TEmax. The recognition error is the Euclidean distance between the reference recognition pattern and the recognition pattern formatted from the input data at the time of the detected sequence. For reference generation, this threshold was set

to TEmax=60*NCOL, where NCOL denotes the number of time camples in the recognition pattern. This is a high value, again to allow consideration of even remotely similar sequences.

Upon detection of a sequence satisfying the above conditions. REFSEL halts processing to initiate repeated audible playout of the detected sound, and then displays the following parameters on a CRT display device:

- (1) SE (the scanning error valley point values) and the occurrence times, for each reference point;
- (2) SQ, the resultant sequence error; and
- (3) TE/NCOL, the recognition error normalized by the number of columns in the recognition pattern.

This processing halt provides the opportunity for a decision as to whether or not to extract scanning pattern and recognition pattern vectors from the detected sound so that they may be averaged into an average reference pattern being stored separately from the original reference pattern. The decision to average should be made only if (1) the sound detected is indeed the target sound; and (2) not too many such detected sounds have already been included into the average reference pattern from this same speaker. Whenever the target sound was detected, note was made of the sequence error and normalized recognition error associated with the occurrence. These notes were later used to monitor the convergence of the various error values, and also to set thresholds used in subsequent processing.

Through keyboard control to REFSEL, program operation can either be continued immediately (thereby not using the detected sequence), or else a new average reference pattern may be formed, and then program operation will resume. Continuing operation means (in either case) that scanning continues for another match with the original (unaveraged) reference pattern. This mode of processing and updating the average reference pattern continues until processing of all of one speaker's data is complete.

After the processing of the data for a given speaker, the following REFSEL options are available:

- (1) No more processing;
- (2) Process another speaker with the original (unaveraged) reference pattern; or
- (3) Process another speaker with the averaged reference pattern, thereby possibly creating yet another average reference pattern.

The option selected depended on (1) whether several detected sounds from the same speaker had been included which caused convergence of the errors, thereby indicating that a stable reference pattern for single speaker had been obtained; and (2) whether detected sounds from several speakers had been included which caused convergence of the errors (to a higher value, usually), thereby indicating that a reference pattern that is stable across speakers had been obtained.

C. Specification of Processing Thresholds

During the procedure described above, many sounds were detected that did not correspond to the actual target reference sound. This was expected since the thresholds were chosen to be very high so as not to miss detecting any actual target sounds. When the "ultimate" averaged reference pattern had been obtained with the above procedure, that pattern was used to process the six speakers' data one last time. During this processing, the normalized errors SQ/(NRP-1) and TE/NCOL were carefully noted when the target sound was detected. The errors so noted were much lower than errors observed when the detected sound was not the target sound (an occurrence of a false alarm).

To complete the specification of a reference pattern, values for SEmax, SQmax, and TEmax were needed for each final average reference pattern for the purpose of processing all design data and all test data to obtain reference occurrence values. For this processing, the thresholds needed to be much

lower to properly exclude false alarms. The values for SQmax and TEmax were selected to be 10 to 20% larger than the largest value of SQ or TE, respectively, observed for detections of target sounds during this processing of the six speakers' data with the final average reference pattern just described. (The exact percentage depended on the relative values of SQ and TE observed for false alarms.) This criterion was followed in an attempt to yield a very low number of false alarms, while allowing some variations due to the processing of yet different speakers. The value of 400 for the scanning error threshold SEmax was retained for use in final processing of all data. This was done to allow for variations in data at the coarticulation level.

D. Reference Selection

The above process was carried out for each of the seven languages in the data base. The result was the specification of 109 potential reference sounds. Of these, 15 were removed from further consideration because they were duplicates of retained references, but having different associated processing thresholds. Table 2 lists the 94 remaining references, their associated processing thresholds, and their source languages.

The complete design data set (from 66 speakers) was processed with these 94 potential reference patterns to determine the numbers of occurrences of each of the reference sounds for each speaker. Then the occurrence values for speakers of each language were summed to yield the language occurrence values shown in columns 5-11 of Table 2.

In the following, N(R,L) will denote the number of occurrences of reference R in all design data from speakers of language L. For example, N(R21,L3) = 8. The following procedure was used to select for further consideration only those potential references that had sufficient language specificity. For each reference, R, its entropy value H(R) was determined.

$$H(R) = -\sum_{A=1}^{\infty} p(L/R) \cdot \log p(L/R)$$
Languages

Table 2
List of 94 Potential References

1	2	3	4	5	6	7	8	9	10	11	12
R	sq	TE	LABEL	LI	L2	L3	L4	L5	L7	LB	B (R)
1	150	15	2 00S	4	11	8	3	15	1	4	2.449
$\dot{2}$	200	15	3 A(N)H	18	28	47	5	29	6	5	2.396
3	50	30	3 ONEE	0	0	4	0	0	Ø	0	0.000
4	50	40	3 SHAUSHEE	0	0	5	0	0	1	0	0.650
3	115	40	3 YEN	13	6	19	2	Ø	8	0	2.037
6	100	40	3 -NDEE	50	22	69	24	49	32	17	2.653
7	100	30	3 SHANH	14	7	39	11	17	8	14	2.564
8	100	30	3 600	7	6	29	6	4	8	2	2.316
9	310	40	3 AHNEE	24	1	13	1	10	21	28	2.347
10	130	45	3 MAYO	ĺ	1	8	1	3	5	0	2.123
11	65	40	3 CHINCHIN	9	0	4	0	1	0	0	0.722
12	35	15	3 KW1-SH(E)	0	.0	3	0	0	0	.0	0.000
13	90	20	3 \$0	9	11	22	16	9	29	11	2.665
14 15	$\begin{array}{c} 65 \\ 100 \end{array}$	15 30	3 S00 3 SHIN	3	2 35	10	1 28	5 36	2 26	$\frac{2}{20}$	$\frac{2.421}{2.750}$
16	50	25	3 NEE	51 47	28	46	29	39	17	16	2.703
17	100	50	3 CHUNG	18	5	15	4	8	24	15	2.589
18	90	30	7 HOHEE	0	ő	10	ō	ő	7	10	0.000
19	50	15	7 MEKORNA	ő	ø	ŏ	ĕ	ŏ	2	ŏ	0.000
20	50	20	7 TAHBEE	ø	ø	ŏ	ŏ	ŏ	2	ŏ	0.000
21	100	40	7 LOOM	21	18	8	31	26	22	12	2.701
22	90	30	7 HOYEA		0	ō	ō	-0	6	0	0.811
23	70	35	7 NEES	18	15	7	17	9	14	7	2.716
24	80	20	7 ESLARMEE	0	Ø	0	Ø	0	4	0	0.000
25	60	25	7 SLAHN	0	0	0	0	0	6	0	0.000
26	80	30	7 BOOD	2	2	Ø	5	6	13	1	2.126
27	70	30	7 SHINALK	0	0	0	0	0	6	0	0.000
28	40	20	7 OE090Z	0	0	0	0	0	2	0	0.000
29	110	30	7 TARREE	0	0	0	0	0	4	0	0.000
30	150	50	2 OWN	13	16	2	7	10	18	9	2.621
31	100	35	7 CHOL	9	11	14	4	12	41	21	2.497
32	60	30	7 00M	3	7	2	7	7	7	1	2.577
33	85	38	7 AHNEE	12	19	13	30	31	25	10	2.687
34 35	100 140	35	7 FOWLYET 7 BOLYAHT	0	0	Ø 1	0	0	7 14	0	$0.000 \\ 0.952$
36	99	45 35	7 HOGANEE	0	1	1	6 1	0	3	0	1.792
37	75	30	7 SHAVAN	0	ø	ò	Ó	0	3	0	0.000
38	70	30	7 GONEES	ø	ø	ő	ő	ő	6	ő	0.000
39	100	30	8 ALTEH	ŏ	0	ø	ŏ	ő	ŏ	3	0.000
40	115	35	8 AYOH	5	3	ĭ	6	5	5	20	2.347
41	100	40	8 ESS0	ő	ő	î	š	2	3	10	1.894
42	60	35	8 INCUSTAR	ő	ŏ	ò	ž	õ	ĭ	7	1.157
43	150	35	8 HETTAH	ĭ	ő	1	<u>-</u>	1	ō	8	1.278
44	80	35	8 POH	$\hat{3}$	ø	i	ŏ	Õ	ö	15	0.913
45	130	35	8 PYOON	71	32	33	42	40	48	59	2.752
46	80	30	8 POOCONAY	0	0	0	0	0	0	3	0.000
47	90	40	8 COTCHEE	θ	0	0	1	Ø	4	7	1.281
48	50	25	8 NOCEE	0	0	0	Ø	0	0	3	0.000
49	90	32	8 01-AH	5	2	0	6	2	1	10	2.226

Table 2 (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
R	SQ	TE	LABEL	Li	F3	L3	L4	Lä	L7	LB	H(R)
50	60	25	4 FOLOTKEH	0	0	0	3	0	θ	0	0.000
51	100	35	4 ESKEE	23	33	19	42	38	10	15	2.664
52	60	25	4 SHANECHEE	0	0	0	3	0	0	0	0.000
53	40	30	4 NARSHER	0	0	0	1	θ	0	0	0.000
54	70	25	4 BORCH	0	0	1	- 3	()	i	İ	1.792
55	40	20	4 YAH	0	()	O	2	0	0	0	0.009
56	40	39	4 CLERYEE	0	0	0	i	- 0	()	0	0.000
57	55	25	4 YEPSKI	0	0	0	:5	0	0	0	0.000
58	85	35	2 CAZR	0	3	0	0	Ð	0	4)	0.000
59	95	30	2 00kHäEH	- 3	3:	4	26	18	3	3	2.219
64)	70	30	2 CHESS	0	6	6	0	0	0	5	0.994
61	35	25	2 STAUNEE	0	2	0	0	0	Ü	O	0.000
62	40	20	2 CHE ENYUH	O	2	+3	0	0	0	O	0.000
63	75	30	2 Budgoler	0	-1	()	0	0	1)	0	0.000
64	15	20	2 MOSKVEE	0	3	()	0	0	()	13	0.000
65	50	25	2 CHEEKEL	()	2	0	()		()	(1	0.000
ti fr	70	25	2 ELTS	17	26	1.4	30	26	15	13	2.730
67	125	45	1 PORGWIAH	1 (45	0	()	0	0	0	0.000
-83	110	40	1 FIFBWON	6	43	6)	()	0	()	0	0.000
49	120	25	1 WHAREE	6	3	()	0	0	0	0	0.811
70	60	20	1 CHOOLET	5	- (1	0	į	0	0	0	0.650
<i>i</i> 1	50	22	1 223801	2	15	0	0	0	0	0	0.000
72	50	1.3	1 -71BAH	?	0	0	- 0	- 0	0	0	0.000
73	85.	30	1 -DVJE	4	0	(1)	0	0	0	0	0.000
74	70	20	1 BAUZAH	3	0	0	0	0	0	0	0.000
7.5	50	25	1 VUNVUN 1 MUT	3	0	0	0	0	- 0	0	-0.000
,° €1	45 60	$\frac{20}{20}$	* * * / *	2	0	0	0	0	0	0	0.000
77 78		30	1 -RTGI	5	0	0	$\frac{0}{3}$	0 2	0	0	1.361
79	465 135	- 33	1 =10 E9 1 =1554H	13	- 0	0	6	- 2	3	1	1.085
(12 (14)	92	26	1 -AVYIEN	3	6	- 0	Ü	1	0	i o	0.650
11.	100	49	T VVEEN	27	1	ï	í	i	ï	0	0.988
4:3	70	30	1 NSPNG	5	- 6	ó	ò	0	ė	ő	0.000
2:3	146	3.5	1 103.1	7	0	ő	ő	1	2	$-\frac{7}{2}$	1.614
81	7,13	1.7	5 04-00FS	\dot{z}	10	ĭ	15	24	- 5	ö	2.069
3.5	125	32	5 8003	6	12	5	6	13	9	9	2.618
86	7.5	28		ï	В	ő	6	7	$\dot{2}$	$\hat{3}$	2.314
äž	60	20	5 TAURU	å	Ü	- 6	ŏ	$\frac{1}{2}$	$\bar{0}$	ő	0.900
83	65	2.3		ö	ő	0	ő	3	ő	ő	0.000
89	60	20	5 HPUNCD	ó	e	Ö	ő	3	ő	ő	0.000
90	55	$\overline{2}_{5}$	5 EFFREIT	ő	ő	0	Ö	3	0	()	0.000
91	33	10		Ö	41	Ö	Ö	3	ő	Ó	0.000
90	100	40	5 ROGREIA.	ő	0	0	ő	ï	Ö	ő	0.000
93	50	20		Ø	e	0	0	$\hat{2}$	0	Ö	0.000
94	45	15		Ö	0	0	2	2	0	0	1.000

The estimated probability of language L given that reference R was detected, p(L/R), is defined to be:

$$p(L/R) = \frac{N(R,L)}{\sum_{\substack{N(R,L)\\ \text{All}\\ \text{Languages}}}}.$$

Table 2, column 12, shows this entropy value for each potential reference. Entropy achieves a maximum (log 7) when the seven probabilities are equal and tends to zero monotonically as one or more of the probabilities tend to one. Hence, a small value for H for a given reference sound indicates an imbalance in the language probabilities and therefore large language specificity.

Table 3 shows the list of 94 potential reference patterns ordered according to increasing entropy. The last 14 patterns listed were deemed to have too little language specificity and were not considered further. The remaining 80 reference sounds were used in all subsequent experiments.

<u>Table 3</u>

Potential Reference Ordered According to Entropy

0rder	Ref.		Label	H(Ref)
1	75	1	WENVUN	0.000
$\hat{2}$	52	4	SHANECHE	0.000
$\overline{3}$	53	4	NARSHEH	0.000
4	46	8	POOGO#AY	0.000
5	12	3	KWI-SH(E)	0.000
6	48	8	MOGEE	0.000
7	91	5	STUNDE	0.000
8	50	4	POLOTKEH	0.000
9	58	2	CAZH	9.000
10	90	5	EEEEEIT	0.000
11	88	5	SCHON	0.090
12	89	5	FFREUN(D)	9,000
13	7.1	1	BAUZAH	0.000
14	64	2	MOSEVEE	0.000
15	92	5	SCHNELL	0.000
16	39	8	ALTEH	\mathbf{o} , eeo
17	37	7	SHAVAN	0.000
18	56	4	CHENYEE	0.00
19	29	7	TAHREE	0.600
29	73	1	-MATE	0.900
21	63	2	BREOLET	0.000
23.	_ 3	3	ONEE	0.000
23	34	7	ESLAUMEE	6.000
24	61	2	STAHNEE	6.000
25	62	2	CHEENYUH	0.090
26	87	5	FAHRT	0.000
27	19	7	MELORNA	0.000
28	93	5 7	MORGAN	0,030
29 39	28 20	7	OBOBOZ TAUBLE	0,090 0,000
39	70	í	MUI	0.000
(i)	72	1	-7BAH	0.000
. 3	33	4	X / II	0.000
34	65		CHITEEL	0.000
35	71	i	-NG001	0.000
35	18		MOHUU	0.000
37	34		FOLLYFE	0.000
36	6.	i	LOUGNBAH	0.000
39	57	4	ATRICA.	0.000
40	77	1	भागा	0.600
41	82	1	NY CHO	0.000
1.2	2.5	7	51 (11)	0.030
43	2	÷	SHUALE	0.000
4.4	68	1	LEEDRON	0.000
45	38	7	600038	0.009
46	70	1	CSCOLET	0.650
47	-1-	3	SHAUSHLE	0.550
48	80	1	WVYTTE	0.630
49	1.1	3	CHINCHIN	0.722

Table 3 (Continued)

Order	Ref.		Labe1	H(Ref.)
59	22	7	HOYEA	0.811
51	69	1	WHAKEE	0.811
52	44	8	POM	0.913
53	35	7	BOIYAHT	0.952
54	81	1	VYIEN	0.988
55	60	2	CHESS	0.994
56	94	5	CATE	1.000
57	79	1	-NWAH	1.985
58	42	8	INCUSTAH	1.157
59	43	8	НЕТТАН	1.278
60	47	8	GOTCHEE	1.281
61	78	1	-NYEO	1.361
62	83	1	DAI	1.614
63	54	4	BORCH	1.792
64	36	7	HOMANEE	1.792
65	41	8		1.894
66	5	3	YEN	2.037
67	84	5 3	NICHTS	2.069
68 69	$\begin{array}{c} 10 \\ 26 \end{array}$	7	MAYO	2.123
70	20 59	2	BOOD OOSHNEH	$\substack{2.126 \\ 2.219}$
71	49	8	OL-VH	$\frac{2.219}{2.226}$
72	86	5	SCHIFF	2.314
73	ĕ	3	QUO	2.314
74	40	8	AYOH	2.347
75	9	3	ANNEE	2.347
76	$\acute{2}$	š	A(N)H	2.396
77	14	3	800	2.421
78	1	2	008	2.449
79	31	7	CHOL	2.497
80	7	3	SHANH	2.564
81	32	7	OON	2.577
62	17	3	CHUNG	2.589
83	30	7	OWN	2.621
84	85	5	MACH	2.648
83	6	3	-NDEE	2.653
86	51	4	ESKEE	2.664
87	13	3	80	2.065
88	33	7	AHNEE	2.687
89	21	7	LOOM	2.701
90	16	3	NEE	2.703
91	23	7	NEES	2.716
92	66	2	EETS	2.730
93	15	3	SHIN	2.750
94	45	- 8	PYOON	2.752

SECTION IV CLASSIFICATION STRATEGY

This section addresses steps 2-4, listed in the introduction of Section III, used to effect language discrimination. The decision function will be formulated and its parameters discussed. The rejection criterion that was applied will be described.

A. Decision Function

A practical decision strategy can be derived by simplification of the optimum decision rule. The optimum decision rule can be expressed in terms of the following definitions:

Let 7 represent the ensemble of possible languages from which the speech data are taken.

Let $X = (x_1 \ x_2 \ , \dots, x_n)^T$, an n-dimensional vector, represent the speech data.

Let $p_i(X)$ represent the probability density function (pdf) of X given the language i.

Let $p_{\check{Z}}$ (X) represent the pdf of X when the language is not known.

Then
$$\mathfrak{r}_{Z}(X) = E \mathfrak{p}_{i}(X)$$

 $i \in Z$

$$= \sum_{i \in Z} p_i(X) P(i)$$

The optimum procedure, meaning the rule that yields minimum expected error, is to choose the language with the greatest likelihood ratio--that is, choose language i where

$$\lambda_{i}(X) > \lambda_{j}(X)$$
 for every $j \neq i$, and where

$$\lambda_{j}(X) = \frac{P(j)P_{j}(X)}{P_{Z}(X)}$$

It is necessary to modify this procedure to incorporate the constraints of the problem and the limitations on the knowledge of the distributions. It is not practical to determine $p_Z(X)$, and P(i) is not known because of the thousands of possible languages and dialects. Hence, the best that can be done is to base decisions on the likelihood function, defined as

$$\Lambda(X/i) = p_i(X).$$

In this study a speaker's data were represented as a sequence of reference sounds,

$$X(t) = [R_1, R_2, \dots, R_{n(t)}],$$

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のでは、100mm

where n(t) is the number of reference sounds detected up to time t, and where it was assumed that R_j and R_j are statistically independent for $i \neq j$. The likelihood function was estimated as

$$\hat{\Lambda}(X/j) = \prod_{i=1}^{n(t)} \hat{\Lambda}(R_i/j),$$

where \hat{A} (R_i/j) is the estimated likelihood of reference R_i given that language j is being considered. The decision function for language j is defined to be

$$d_{j} = -\sum_{i=1}^{n(t)} \log \hat{\Lambda}(R_{i}/j),$$

the negative of the sum of log-likelihoods for all detected reference sounds.

B. Estimation of Likelihoods

The estimation of reference likelihoods used to evaluate the decision functions was accomplished as follows. The numbers of occurrences of each reference in each design speaker's data (two-minute speech segments) were determined (using the associated processing thresholds). Then the occurrences of each reference of a given language were summed to obtain the language occurrence values, N(R,L) (See Section III.D.). Defining M(R,L) as:

$$M(R,L) = \frac{N(R,L) + N_{min}}{\sum_{R \in Ferences}}$$
All

the likelihood estimate is defined to be:

$$\hat{\Lambda} (R_i/j) = \frac{M(R_i,L)}{\sum_{\text{M(R,L)}} M(R,L)}$$
All Languages

 N_{min} (= 2) is used to minimize the effects of rarely occurring references.

C. Decision Rule

To evaluate the decision function for a test speaker, the two-minute segment of speech data from that speaker was processed to count the

occurrences of all reference sounds, using the associated processing thresholds. The corresponding log-likelihoods were summed and negated to obtain the decision function values $\mathbf{d_j}$. The decision rule is to choose the language that yields the minimum decision function value.

D. Rejection Criterion

When the minimum decision function value is much smaller than the next smallest value, a decision can be made with high confidence that the decision is correct. However, when the smallest and next smallest values are close, one cannot have as much confidence in the resulting decision. Hence, the following rejection criterion was invoked. First select a rejection threshold, then for the test speaker, decide that language yielding the smallest decision function value, provided the next smallest decision function value exceeds the smallest by at least the value of the threshold; otherwise, do not make a decision (reject the speaker).

For a given threshold, a certain percentage of speakers are not classified (rejected), and a certain percentage of classified speakers are correctly classified. An operating curve of percent correct classification versus percent speaker rejection can thus be plotted. Such results are presented in the next section.

SECTION V CLASSIFICATION RESULTS

A. Seven-Language Results

Using the set of 80 reference sounds described in Section III as the reference file with the decision rule and rejection criterion described in the previous section, the 65-speaker, 7-language test set was processed. The resulting decision function values are shown in Table 4. Also shown in that table (last column) is the difference between the minimum decision function value and the next smallest decision function value, for each speaker. It is this value that determines whether or not a decision is to be made for the speaker. The resulting Percent-Rejection, Percent-Correct operating curve is shown in Figure 2. It can be seen that, with no rejects (that is, a language was assigned to every test speaker), 43% of the 65 speakers were correctly classified. It is further noted that at a rejection rate of 70%, 80% correct classification of the remaining 20 speakers was achieved.

Remembering that many of the seemingly good reference sounds yielded fairly small numbers of occurrences with the associated processing thresholds that had been assigned (See Table 2, Section III), it was decided to increase (loosen) these thresholds, reprocess the design data to obtain revised likelihoods, and reprocess the test data for another evaluation. For this reprocessing, SQmax for each reference was increased by a factor of 1.5, and TEmax was increased by a factor of 1.33 for each reference sound. The resulting decision function values are shown in Table 5, and the resultant operating curve is shown as Curve B in Figure 3. (Curve A from Figure 2 is reproduced in Figure 3, for comparision.) The improvement is dramatic: 62% correct classification was attained when no rejects were allowed, and 100% correct classification was achieved with a reject rate of only 68%.

Table 4

Decision Function Values

Ling	SPKR	L1	ſŞ	L3	<u>L</u> 4	L5	L7	LB	FWIN	OIFF
1	1	15.70	17.81	16.01	19.12	15.60	19.48	17.12	5	0.106
ī	ě	32.37	29.16	27.52	41.22	26.76	40.61	43.55	5	0.760
1	3	26.62	28.71	23.77	38.65	26.72	34.06	35.31	3	2.851
1	4	25.47	28.41	18.14	33.27	23.47	27.32	29.16	3	5.332
1	5	44.57	59.45	41.96	68.03	50.35	51.82	23.55	5	2.610
1	6	4.27	4.14	2.32	5.13	3.34	5.78	5.29	3	1.025
1	7	17.95	25.63	25.72	27,19	26.93	28.51	28.68	1	7.682
1	8	20.46	26.51	23.93	35.70	26.34	34.39	35.42	1	3.475
1	9	1.61	8.11	8.74	7.28	8.30	8.46	A.30	1	5.677
1	10	20.73	20.06	15.79	29.12	22.10	29.89	53,60	3	4.273
						_				
5	1	32.77	19.21	25.31	26.83	17.11	34.42	37.61	5	2.104
2	5	42.03	27.57	43.07	24.83	24.07	36.44	41.93	5	0.756
5	3	37.16	31.55	35.26	36.42	30.95	30.26	31.74	7	0.686
5	4	33.78	15.51	31.69	17.57	18.59	33.91	53.55	5	2.064
5	5 6	6.26	2.79	5.61	3.87	2.20	5.89	6.01	5	0.589
2	0	15.72	13.45	11.30	19.09	11.80	50.58	19.79	3	U . 494
3	•	28.45	21.02	31 1 1 1	28 <u>.</u> 89	24.71	31.74	35.91	د	0.074
3	1 2	74.86	79.64	21.10 60.80	90.55	77.40	81.92	94.15	3	14.064
3	3	29.79	26.54	18.95	34.83	27.01	38.49	41.31	3	7.587
3	4	42.29	35.74	24.52	42.77	35.41	43.81	51.75	3	10.892
3	5	32.73	34.52	24.73	41.07	35.79	24.74	33.21	3	0.014
3	6	43.68	49.23	31.24	57.39	45.94	53.29	57.61	3	12.436
3	7	30.81	35.41	21.16	40.37	32.40	32.28	34.37	3	9.650
3	8	28.51	39.04	25.40	45.40	31.55	31.45	33.90	3	3.117
3	9	36.11	42.01	33.10	48.00	34.28	36.16	36.55	3	1.181
3	10	26.19	23.54	17.00	28.89	23.08	32.49	32.24	3	6.083
4	1	18.99	14.70	46.18	21.85	14,44	17.47	20.52	5	0.265
4	5	25.29	13.04	24.06	12.62	11.71	23.19	22.88	5	0.907
4	3	39.47	25.78	34.60	32.91	28.66	39.44	43.92	5	2.879
4	4	12.03	6.02	13.07	5.77	6.01	11.15	12.71	4	0.243
4	5	54.89	41.29	58.33	44.56	42.11	63.52	61.18	2	0.821
4	6	57.10	37.89	56.64	36.73	38.76	54.33	52.41	4	1.160
4	7	5.80	5.53	7.06	5.98	7.37	7.93	9.16	5	0.264
4	8	37.20	28.23	27.90	35.54	28.00	37.33	39,30	5	0.098
4	9	5.06	4.68	5.09	3.07	3.70	3.04	4.80	7	0.036
4	10	50.69	37.17	41.91	ے 0 ۔ 37	36.39	42.27	55.39	5	0.634
4	11	25.11	16.52	22.54	15.88	17.31	23.19	22.42	4	0.646
4	12	18.91	15.16	18.08	16.31	16.04	23.14	19.47		0.883
4	13	52.44	39.32	52.14	34.95	41.64	51.70	44,21	4	4.374
4	14	103.09	71.64	90.37	65.59	69.47	104.24	102.20	4	3.686

Table 4 (Continued)

LNG	SPKP	L1	FS	L3	L 4	١ 5	∟7	L.B	FWIA	DIFF
5	1	35.86	37.62	36.26	43.60	32.17	33.80	35.78	5	1.625
5	è	17.95	25.55	18.21	27.04	17.39	20.29	17.31	ď	0.083
5	3	26.01	20.36	21.90	24.45	19.68	51.11	30.33	5	u.676
S	4	22.97	11.37	18.08	16.28	12.00	24.50	24.48	ے	0.624
5	5	23.83	23.71	23.28	25.76	19.90	28.63	29.97	ל	5.320
5	6	39.96	39.57	35.71	43.91	51.05	44.89	40.95	5	4.657
٠ 5	7	30.51	30.78	17.92	37.85	29.00	40.24	41.90	5	11.075
5	8	58.26	23.42	20.10	38.5H	20.94	38.14	37.82	3	0.842
5	9	8.54	19.50	12.75	و0.38	13.40	12.33	11.04	1	2.444
5	10	54.74	47.84	45.71	56.24	40.68	58.49	54.57	ל	5.021
7	1	32.01	34.16	29.05	35.24	30.35	25.98	26.87	7	0.890
7	5	16.99	25.97	20.62	25.44	24.08	17.12	23.52	1	0.135
7	3	18.01	17.52	13.61	17.50	14.90	20.48	18.67	5	1.288
7	4	21.07	28.42	26.90	26.89	24.12	18.89	19.40	7	0.504
7	5	50.47	79.84	65.23	75.06	60.31	59.00	47.87	ď	2.003
7	6	39. 00	53.68	39.66	61.71	44.15	49.18	42.04	1	0.666
7	7	47.36	67.50	54.96	69.45	53.39	52.24	44.30	8	3.060
7	8	22.18	26,99	24.40	27.28	22.83	25.03	55.02	ø	0.135
8	1	12.40	14.28	13.23	15.06	12.15	12.51	10.49	В	1.654
8	2	18.84	11.04	17.56	12.32	11.60	22.14	19.82	ہے	0.567
8	3	17.33	10,51	14.15	13.23	10.95	13.50	16.12	ہے	0.440
8	4	16.67	23.86	18.89	27.35	19.31	15.45	16.30	1	0.848
8	5	17.30	50.55	18.49	22.93	18.48	17.77	10.00	H	6.643
8	6	27.45	28.72	24.81	30.72	24.91	27.13	19.63	8	5.181
8	7	56.48	54,08	49.34	58.67	53.87	55.48	61.52	5	4.531

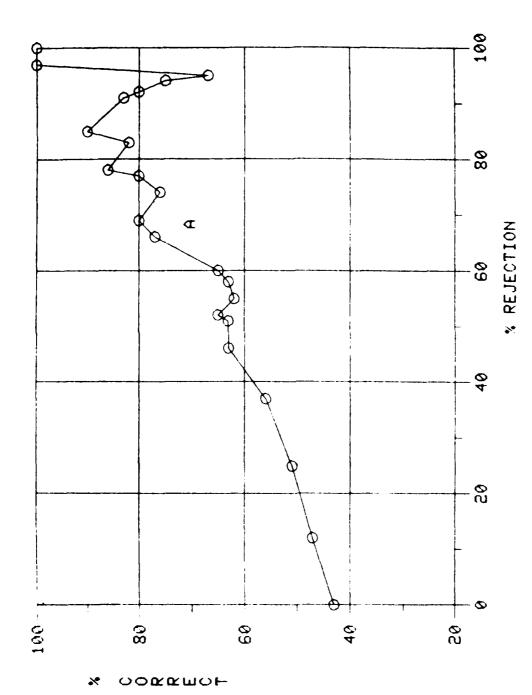


Figure 2 Classification Performance Operating Curve

<u>Table 5</u>

Decision Function Values, Second Experiment

LNG	SPKR	Ł1	F5	L 3	<u>L</u> 4	L 5	L 7	L8	LMIN	D1FF
1	1	61.04	66.77	57.11	70.54	59.01	65.46	65.78	3	1.903
i	5	60.87	58.71	59.87	74.63	57.50	79.44	78.97	5	1.208
i	3	102.79	118.19	105.68	132.86	110.48	116.35	121.84	1	2.885
i	4	93.35	107.10	101.17	115.20	99.36	103.18	110.27	1	6.014
ī	5	116.26	134.63	116.08	135.83	120.84	123.89	123.58	3	0.186
1	6	63.41	74.06	70.60	78.86	71.80	85.31	83.68	1	7.195
ì	7	90.66	120.47	123.42	114.06	107.44	118.85	122.98	1	16.777
1	8	84.15	108.29	95.90	116.77	99.16	107.72	112.76	1	11.742
i	9	37.29	56.38	61.05	50.55	51.87	54.58	59.03	1	13.262
1	10	75.77	81.68	83.00	95.30	76.82	100.25	97.03	1	1.053
2	1	66.60	49.86	59.32	62.75	51.48	69.75	68.15	2	1.626
2	5	135.29	103.77	139.07	97.36	95.46	135.65	141.03	של	1.901
5	3	155.18	129.81	150.34	133.40	129.00	137.49	146.71	5	0.804
2	4	115.78	81.40	97.39	86.66	84.79	101.69	103.50	5	3.390
2	5	44.25	35.83	50.22	34.08	33.88	42.97	47.87	5	0.195
5	6	70.34	61.11	59.75	74.43	61.16	78.15	/9.00	5	1.331
2		101 14	90 7 3	0E 70	00.30	90 15	49.92	100 58	4	5.439
3 3	1	101.16	89.72	85.78	90.29	90.16 163.61	167.12	100.58		18.107
	3	163.45	161.92	143.81	175.02 81.74	67.76	77.71	78.43	3	9.930
3	4	70.09	66.39	56.46	108.93	91.97	113.80	109.64	3	2.825
3	5	101.92	95.51	89.14	106.75	94.94	87.68	96.83	1	1.189
3	6	86.37	102.47	87.56 102.56	131.91	115.69	128.53	136.97	5	7.851
3	7	102.69	102.36	75.68	110.25	100.62	105.83	106.82	5	24.945
3	8	86.70	88.38	67.59	102.77	96.20	89.86	93.06	3	10.604
3	9	101.47	98.56	90.67	107.03	97.01	102.96	107.51	3	6.534
3	10	17.20	77.48	54.65	68.81	77.24	87.06	87.24	3	22.534
		6 3		· -	24.4	77.0	03.44	04.8		0 070
4	1	93.14	74.80	80.67	81.62	73.86	92.63	91.82	5	0.939
4	5	95.01	88.59	105.61	86.61	90.99	86.77	93.68	4	0.164
4	. 3	131.47	106.22	122.32	100.00	103.14	122.59	129.04	4	3.135
4	4	75.55	56.70	74.12	50.75	57.58	68.61	74.80	4	5.949
4	5	198.96	177.09	202.19	164.77	161.74	204.24	203.56	5	3.031
4	6	184.18	139.98	168.06	129.38	138.99	161.60	172.67	4	9.613
4	7	54.35	45.78	52.73	39.88	45.30	48.00	47.62	4	5.41/
4	8	99.33	78.05	85.57	84.22	76.72	97.29	102.12	5	1.328
4	9	64.80	52.88	64.45	40.35	48.85	55.54	57.18	4	8.515
4	10	105.26	168.29	189.71	150.78	166.71	162.20	192.04	4	11.416
4	11	89.07	69,67	85.43	59.40	62,79 80,16	82.53 86.04	84.65	4	5.395 1.909
4	12	82.14	84.05	84.58	82.07	160.73	174.57	86.56 184.05	ت 4	b.277
4	13	196.85	169.39	191.46	152.46			316.49	4	
4	14	359.30	283.08	316.14	262.38	267.30	312.78	110.47	•	4.913

Table 5 (Continued)

LNG	SPKR	L1	ΓS	٤3	L4	L 5	L7	L8	LMIN	DIFF
5	1	119.40	114.08	114.38	116,25	106,31	117.21	121.06	5	7.768
5	5	105.36	110.45	98.88	104.07	99.09	98.89	100.70	3	0.006
5	3	59.54	53.01	55,37	58,32	49.76	68.29	69.38	5	3.248
5	4	48.13	32,57	42.39	36.91	31.47	51.89	51.96	5	1.100
5	5	63.61	63.07	59.65	64.55	53.33	71.05	69.19	5	6.315
5	6	79.42	66.04	65.18	76,28	61.36	81.72	71.77	5	3.828
5	7	109.38	98.54	95.24	115.06	89.48	131.49	115.77	5	5.758
5	8	69.21	67,61	61.03	92,44	65.79	92.17	83.09	5	4.759
5	9	70.38	74.49	82.74	70.41	67.12	75.49	74.43	5	3.259
5	10	137.85	112.32	124.16	119.31	110.41	131.09	124.86	5	1.915
7	1	115.60	112,09	111.88	109.88	110.66	96.24	112.20	7	13.641
7	5	111.79	138.80	121.56	138.12	125.04	107.71	151.94	7	4.079
7	3	94.58	68,42	86.81	85.95	79.51	8R.49	82.40	ל	2.893
7	4	116.74	111.03	125.84	102.68	99.61	100.38	109.32	5	0.772
7	5	240.42	275,53	260.59	265.93	235.26	555.08	218.59	В	3.493
7	6	123,28	155.18	109.67	155.80	118.21	131.30	107.39	8	2.275
7	7	156.16	178,02	154.52	188.43	151.29	166.43	147.05	ರ	4.240
7	8	77,16	75.53	77.39	77.30	67.59	79.45	72.62	5	5.036
			_							
8	1	74.97	67.47	71.26	62.08	67.21	69.76	65.06	4	2.984
8	š	144.15	122.84	125.30	127.07	125.05	132.23	123.73	ے	0.888
8	3	94.45	71.30	82.93	74.16	78.34	83.86	84.25	5	2.861
8	4	74.09	67,01	59.34	74.16	67.98	57.86	60.44	1	1.484
8	5	101.49	101.27	94.58	105.98	90.86	104.47	86.17	ಕ	4.685
8	6	74.94	73.22	74.56	73.90	63.29	10.78	61.32	ð	1.463
ь	7	166.87	161.17	163.13	158.42	152.54	162.53	158.01	5	5.477

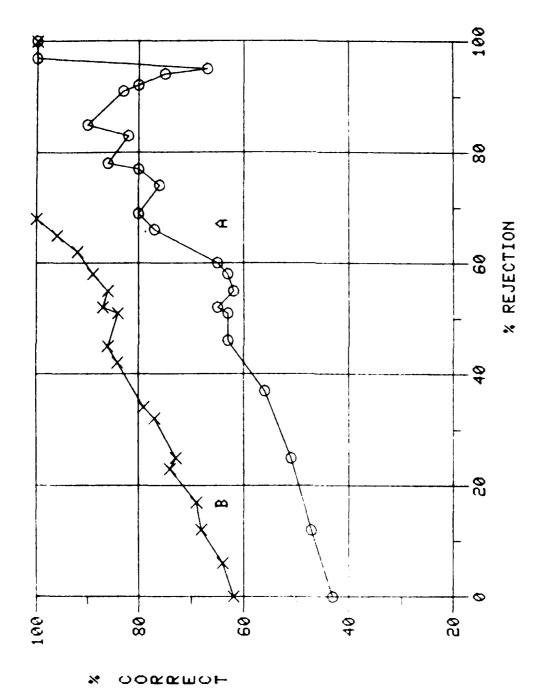


Figure 3 Performance Curve, Second Experiment

A second reprocessing was accomplished in the same manner as above, increasing SQmax, for each reference sound, by a factor of 2.0 from the original values and increasing TEmax by a factor of 1.5. The decision function values obtained are shown in Table 6, and the operating curve is shown as Curve C in Figure 4. (Curves A and B from the previous figures are reproduced there for comparison.) The no-reject correct classification rate is up to 74%. However, and more importantly from an operational point of view, the number of incorrect decisions avoided by rejection increases much less slowly with increasing rejection rate, so that 88% rejection is required to achieve 100% correct classification of the remaining speakers.

A third and final reprocessing was accomplished, increasing SQmax by a factor of 3.0 and TEmax by a factor of 2.0 from the original values, for each reference sound. The resulting decision function values are shown in Table 7, and the operating curve is shown as Curve D in Figure 5. (Curve C from Figure 4 is reproduced there for comparison.) Performance here has clearly deteriorated.

In summary, four sets of processing thresholds were used in four otherwise identical experiments. This sequence of experiments allowed specification of the set of processing parameters which provides acceptable classification performance, namely those parameters yielding operating curve B of Figure 3. The original specification of parameters described in Section III apparently imposed requirements which were too stringent to allow detection of many acceptable variations of the reference sounds. The parameters yielding Curves C and D, on the other hand, allowed detection of too many sounds which lacked sufficient language specificity to provide operational classification performance.

To ϵ stablish performance as a function of particular languages, Table 5 was used to determine the percentage of correct classification for three representative values of rejection threshold. (Table 5 shows decision function values that yielded Curve B.) These results are shown in Table 8,

Table 6

Decision Function Values, Third Experiment

LNG	SPKR	L 1	٢2	L3	L 4	L5	∟7	L8	LMIN	DIFF
1	1	116.08	121.92	112.70	133.23	115.72	125.94	125.41	3	3.026
i	Ş	116.54	126.31	118.80	140.84	121.38	138.06	136.67	i	2.257
i	3	228.87	251.58	245.17	264.17	246.38	244.64	257.92	i	15.772
i	4	196.60	226.14	216.23	235.66	219.30	217.20	235.52	i	19.634
ī	5	205.38	237.45	216.26	245.18	225.04	224.77	240.21	1	10.882
ī	6	155.54	176.21	166.60	191.41	172.81	192.17	201.28	ī	11.065
1	7	177,52	216.18	205.70	214.83	201.61	204.90	222.70	ī	24.090
1	8	151.06	183.90	162.68	188.33	172.66	174.74	186.55	1	11.620
1	9	90.78	109.29	105.44	104.84	103.39	106.75	118.65	1	12.609
1	10	162.09	177.33	170.28	194.20	170.47	191.82	193.98	1	8.191
5	1	121.96	102.65	116.48	118.11	106.83	128.98	126.69	ے	4.183
ءَ	ş	213.68	180.14	208.99	183.65	171.44	222.77	227.38	Š	8.705
5	3	261.89	252.80	268.30	246.37	245.38	255.19	275.32	5	0.995
2 ع	4	180.18	143.90	164.57	148.56	150.80	163.30	169.26	جَ	4.657
ج	5	79.54	66.47	82.14	65.73	66.13	76.58	81.15	4	0.393
5	6	126.68	123.54	118.84	142.73	121.15	141.73	132.52	3	2.311
_	Ü	120.00	123.34	110.04	146 • 13	121.13	141.73	130.30	,	2.311
,		170 74	10/1 32	171 76	407 47	174 32	170 (/	100 10	,	a 377
3 3	1	178.36	184.23	171.35	183.17	176.23	179.66	190.19	. 5 5	4.877
3	2 3	290.36	290.78 134.48	269.23 119.23	314.25	291.06 129.83	294.11 139.93	307.08 124.55	3	21.133
3	4	153.44	143.13	133.39	162.19 169.82	146.19	164.05	158.65	3	9.738
3	5	141.24	156.53	138.48	156.19	147.38	139.72	144.82	3	1.240
3	6	234.60	266.01	233.81	275.16	247.04	275.83	295.65	3	0.786
3	7	176.63	182.75	154.04	201.21	182.84	108.63	186.93	3	22.591
3	Ŕ	149.00	167.82	139.12	180.63	157.54	153.45	164.29	3	9.883
3	9	176.27	173.76	157.15	188.90	168.25	178.52	181.84	3	7.992
5	10	114.95	121.20	98.28	129.87	114.87	127.92	124.27	3	16.583
2	•	1144/3	121.20	,,, <u>,</u> 20	(E 7 • O ·	114607	121,72	164461	,	10.30
4	1	150.83	133.76	143.03	143.19	132.27	156.58	159.59	5	1.496
4	2	184.16	175.86	192.28	168.87	176.28	172.16	190.71	4	3.288
4	3	224.01	216.98	220.32	212.79	211.35	229.84	235.86	כ	1.432
4	4	183.50	159.73	185.87	150.84	160.40	171.43	183.33	4	8.884
4	5	356.46	332.56	367.05	329.71	316.86	374.46	372.61	5	12.851
4	6	330.05	287.55	329.29	281.04	288.39	318.75	334.60	4	6.512
4	7	144.57	130.22	152.43	120.52	128.79	132.41	129.45	4	8.272
4	8	165.74	151.22	155.50	159.70	145.45	164.75	168.10	5	5.174
4	9	154.83	136.91	148.24	119.42	126.54	149.25	151.97	4	7.116
4	10	318.59	303.16	323.29	283.24	294.50	294.00	350.AZ	4	10.756
4	ĩ 1	156.63	132.93	150.39	128.76	132.35	155.13	157.83	4	3.596
4	12	184.14	178.46	186.26	173.27	170.37	181.24	180.36	5	2.405
4	1.3	302.49	280.39	306.29	264.85	278.58	284.25	302.12	4	15.737
4	14	595.43	548.95	608.22	522.19	529.81	590.94	612.79	4	7.020

Table 6 (Continued)

LNG	SPKR	L 1	F.5	L 3	L 4	L 5	∟7	L8	LMIN	DIFF
5	1	225.98	224.70	232.19	231.74	221.10	225.61	230.52	5	3.600
5	2	194.74	808.98	194.70	200.87	190.74	192.20	196.09	5	1.460
5	3	105.62	99.04	98.67	104.58	91.81	110.58	113.44	5	6.863
5	4	96.72	82.52	91.85	83.67	77.92	98.11	95.85	5	4.600
5 5	5	136.13	131.49	135.75	137.13	120.60	145.36	140.64	ל	10.892
5	6	147.47	133.79	135.68	147.34	127.11	151.72	135.41	5	6.672
5	7	192.78	185.58	179.04	213.30	176.81	215,65	203.34	5	2.239
5 5	8	158.72	161.87	150.59	193.47	160.71	182.60	182.16	· 3	8.128
5	9	148.32	149.77	154.67	152.03	141.40	156.64	152.25	5	6.426
5	10	232.39	210.59	223.81	219.70	548.85	237.37	242.89	5	1.773
7	1	217.03	217.00	232.24	212.89	215.98	197.62	208.33	7	10.709
7	ė	216.85.	257.62	234.85	251.49	242.76	213.83	258.78	7	3.018
7	3	171.87	168.85	169.08	167.06	160.00	156.56	162.44	7	3.446
7	4	240.07	234.94	246.88	227.85	226.06	207.65	228.71	1	18.415
7	5	383.32	421.49	405.06	428.10	3/8.49	348.17	359.39	1	11.224
7	6	211.24	228.17	199.31	272.14	213.17	214.49	142.33	8	6.980
7	7	240.31	273.38	241.25	293.86	249.58	244.79	242.97	1	0.943
7	8	141.07	145.23	141.70	151.18	139.18	138.16	152.72	8	5.432
8	1	145.48	144.69	140.83	141.48	139.45	139.35	135.50	ö	3.853
8	5	233.95	228.09	223.06	225.25	223.34	225.04	217.11	8	5.950
8	3	187.03	168.52	178.99	172.85	174.50	176.74	172.06	دے	3.538
8	4	147.28	148.04	145.13	157.90	147.49	126.47	129.24	7	2.778
8	5	161.40	163.81	162.57	177.11	153.61	158.35	147.42	ø	6.184
8	6	144.51	147.95	156.20	150.93	137.64	148.87	137.08	8	0.554
8	7	287.71	88.195	291.42	289.90	274.21	287.20	285.07	5	10.857

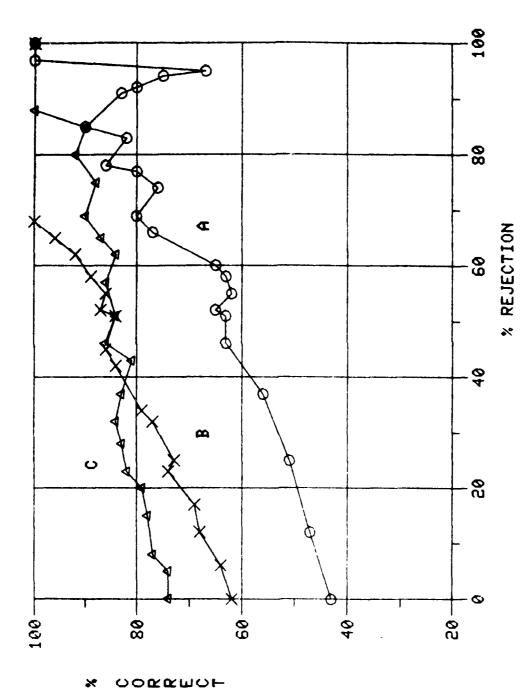


Figure 4 Performance Curve, Third Experiment

Table 7

Decision Function Values, Fourth Experiment

										
LNG	SPKR	L1	ΓS	L 3	L4	L5	∟7	L8	LMIN	DIFF
		744 74	774 06	777 07	705 64	747 74	7 4 7 9 4	700 17	•	11 115
1	1	361.76	376.95	372.87	395.62	383.71	387.89	390.17	1	11.115
1	5	403.98	418.45	413.79	428.92	420.12	430.79	435.87	1	9.809
1	3	635.75	665.85	654.57	686.79	665.64	634.11	645.25	7	1.640
1	4	600.05	635.66	623.39	666.91	644.08	629.80	650.01	1	23.347
1	5	536.77	583.81	558.18	608.94	594.90	554.98	580.54	1	18.208
1	6	463.17	474.13	482.91	482.42	479.65	506.20	531.04	1	10.956
ī	7	479.11	506.61	497.30	498.71	491.62	499.54	514.55	1	12.505
i	8	401.77	428.99	408.10	427.89	420.41	414.32	423.39	i	6.324
					_					
1	9	386.40	391.83	395.99	385.81	391.99	395.24	405.62	4	0.586
1	10	445.27	464.00	450.96	465.25	456.40	475.59	473.04	1	5.691
2	1	302.48	283.85	299.59	306.73	299.12	315.00	312.56	2	15.272
ē	ş	532.76	499.25	528.85	496.29	488.97	546.64	558.58	5	7.324
۶	3	604.83			585.39	592.86	605.34	627.56	4	7.467
			593.75	603.69						
5	4	480.67	454.77	468.82	465.62	461.46	473.85	470.81	2	6.688
5	5	227.52	209.04	234.44	208.67	211.92	226.34	234.33	4	0.378
5	6	351.06	364.65	345.49	383.53	361.63	371.64	368.21	5	5.570
3	1	467.66	477.60	457.88	476.77	470.55	485.43	466.48	3	9.778
3	2	662.47	678.03	655.55	696.79	685.60	677.93	694.59	3	6.423
3	3	310.14	321.15	297.73	347.79	320.04	312.24	307.79	3	10.068
3	4	329.99	328.65	310.55	344.96	328.08	339.12	338.33	5	17.531
3	5	289.91	318.39	297.05	326.05	317.00	295.58	304.80	ī	5.773
3								782.77		
	6	683.78	733.03	702.75	730.80	716.97	730.45		1	18.944
3	7	375.68	400.30	361.47	432.84	406.19	388.06	386.88	3	14.210
3	8	374.95	367.04	359.65	387.50	301.59	386.43	345.04	3	15.283
3	9	406.45	426.56	403.17	434.44	418.66	415.26	415.25	3	3.284
3	10	389.11	400.66	371.96	402.08	391.57	402.02	411.07	5	17.150
4	1	387.61	371.15	387.56	317.54	370.67	390.78	411.50	5	0.481
4	ż	493.40	485.89	496.30	485.72	491.32	492.17	504.37	4	0.167
4	3	535.55	541.90	534.49	539.42	536.33	550.34	557.47	5	
										1.061
4	4	546.07	522.99	554.09	524.00	256.50	541.39	563.AB	د	1.007
4	5	859.72	861.18	871.91	861.19	845.95	863.69	842.24	ל	13.784
4	6	796.29	755.38	801.63	743.71	758.94	811.32	844.06	4	11.664
4	7	407.56	390.86	410.50	387.84	369.26	401.74	349,45	4	1.417
4	Я	450.92	419.72	438.11	427.64	421.63	451.10	453.60	ے	1.902
4	9	461.93	449.35	455.80	423.19	429.85	467.60	481.33	4	6.664
4	10	723.54	728.16	750.98	703.63	710.73	720.32	762.75	4	7.102
4	11	445.15	425.55	442.04	413.35	416.03	448.82	451.81	4	2.702
4		489.01				465.61			4	
	12		484.29	484.30	463.66		498.35	511.04		1.946
4	13	683.97	678.82	702.71	684.37	678.58	685.44	694.85	ל	0.240
4	14	1203.84	1288.10	1301.28	1247.94	1248.51	1209.90	1338.98	4	0.570

<u>Table 7</u> (Continued)

LNG	SPKR	L1	F5	L3	L4	L 5	L7	L8	LMIN	DIFF
5	1	590.46	582.38	609.45	589.90	575.10	592.67	605.92	5	7.281
5	2	458.98	478.92	454.21	469.49	454.44	465.90	467.14	3	0.231
5	3	316.19	317.16	318.31	321.19	305.35	329.67	329.26	5	10.837
5	4	326.72	307.31	323.51	316.90	310.44	340.73	341.22	حَ	3.126
5	5	364.97	353.31	359.60	358.55	344.57	379.39	374.85	5	8.741
5	6	449.80	424.64	441.77	430.89	413.32	453.87	427.92	5	11.310
5	7	506.69	498.53	495.86	515.33	490.86	531.98	513.92	5	5.002
5	8	393.59	396.82	385.57	429.32	403.65	405.42	406.33	3	8.022
5	9	468.03	462.84	475.63	462.54	444.08	480.28	469.43	5	18.465
5	10	469.13	456.33	458.90	478.43	461.51	463.67	487.34	2	2.572
										,
7	1	525.29	529.79	544.76	528.35	528.59	519.04	527.23	7	6.253
7	5	520.41	568.83	538.13	560.62	556.98	503.42	552.83	7	16.986
7	3	409.72	412.67	409.84	404.32	398.87	348.96	399.46	ל	U.096
7	4	579.71	576.85	588.17	591.10	577.78	552.71	553.37	7	0.662
7	5	746.55	811.61	774.65	799.66	764.14	714.25	722.91	1	6.661
7	6	398.84	421.20	402.63	451.65	413.82	392.19	381.38	ರ	10.804
7	7	521.70	551.32	526.25	562.29	536.59	512.11	500.04	ь	12.074
7	8	363.53	380.68	366.76	386.52	374.47	374.20	376.25	1	3.229
ь	1	326.00	336.30	322.91	342.40	327.04	329.16	319.73	ь	3.240
ರ	5	509.59	520.49	501.93	531.65	516.12	511.25	493.40	8	0.446
8	3	409.47	396.79	406.71	404.49	413.40	400.74	401.62	ے	3.946
8	4	334.56	349.44	342.69	357.8v	350.70	323.81	324.91	7	1.102
8	5	391.11	405.33	393.65	414.63	398.56	385.56	385.03	8	0.537
ь	6	355.62	354.92	358.68	359.21	351.98	360.68	349.89	ಕ	2.097
В	7	639.41	660.84	653.27	659,66	644.30	645.68	655.42	1	4.892

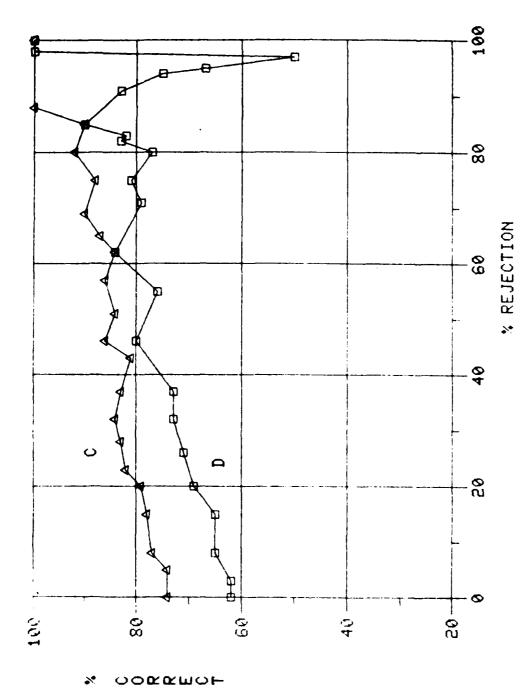


Figure 5 Performance Curve, Fourth Experiment

Table 8
Classification Accuracy as a Function of Language

Rejection									
Thresholds		0.0			1.4			3.0	
Language	#Cor	#Dec	2Cor	#Cor	#Dec	%Cor	#Cor	#Dec	%Cor
L1	7	10	70	6	7	86	5	5	100
L2	2	6	33	2	3	67	1	1	100
L3	9	10	90	9	9	100	8	8	100
L4	10	14	71	9	11	83	9	10	90
L5	8	10	80	7	8	88	6	7	86
L7	2	8	25	2	7	29	2	5	40
L8	2	7	29	2	6	33	1	2	50
Totals	40	65	62	37	51	73	. 32	38	84
Rejection									
Rate			0%			22%			42%

along with the rejection thresholds used and resultant rejection rates. This table shows, for each case, and for each language, the number of decisions made (that is, the number of speakers not rejected), the number of these decisions that yielded the correct speaker, and the corresponding percentage correct. This table demonstrates the improvement in classification performance with increasing rejection rate for each language, and indicates the relatively poor performance attained with languages L7 and L8. This poor performance is due largely to the lack of familiarity with the sound of these languages, compared to the familiarity with the other languages gained in the previous research studies. This lack was a hindrance in the selection of appropriate reference sounds for these languages.

B. Five-Language Results

To consider further the effect that including additional languages into the data base had upon classification accuracy, the following experiment was performed. Only the 54 reference sounds selected from speakers of L1, L2, L3, L4, and L5 were used. The processing thresholds used were those of the first reprocessing (which yielded Curve B of Figures 3 and 4). The above design and test procedures were then followed, testing only the 50 test speakers from languages L1, L2, L3, L4, and L5. The resulting decision function values are shown in Table 9, and the operating curve is shown as Curve E in Figure 6. Curve B of Figure 3 and 4 is reproduced there for comparison. It is clear that performance decreased when the additional languages L7 and L8 were included. The no-reject classification accuracy decreased from 72% to 62%, and 68% rejection was required rather than 56% to yield 100% correct classification.

<u>Table 9</u>

Decision Function Values, Five-Language Experiment

1	LivG	5PK)	₹ L1	Ľ2	L 3	<u> </u>	Lo	LMIN	UIFF
1	1	1	61.04	a6 77	57 11	70 54	59 n1	χ.	1 903
1									
1								_	
1									
1		5		-					
1 7 90.66 120.47 123.42 114.06 107.44 1 16.777 1 8 84.15 108.29 95.40 116.77 94.16 1 11.742 95.40 116.77 79.16 1 11.742 1 4 37.29 56.38 61.05 50.55 51.67 1 13.262 1 10 75.77 81.68 83.00 95.30 76.62 1 1.053 2 1 1.053 2 1 10 75.77 81.68 83.00 95.30 76.62 1 1.053 2 1 1.053 2 1 1 1.053 2 1 1 1.053 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1	6							
1	1	7		_					
1 10 75./7 81.68 83.00 95.30 70.02 1 1.053 c 1 1 60.60 49.80 59.52 02.75 51.48 2 1.626 c 1 1 50.60 49.80 59.52 02.75 51.48 2 1.626 c 1 135.29 103.77 139.07 97.36 95.46 5 1.901 c 3 155.18 129.81 150.34 153.40 129.00 5 0.804 c 4 115.78 51.40 97.59 86.66 84.79 2 3.3390 c 5 44.25 35.83 50.22 34.08 35.68 5 0.193 c 6 70.54 61.11 59.78 74.43 61.16 5 1.551 d 1 101.16 69.72 85.78 90.29 90.16 3 3.959 d 2 165.45 151.92 145.61 175.02 165.61 5 18.107 d 3 70.09 86.39 56.46 81.74 67.76 3 9.330 d 4 101.92 95.51 89.14 108.93 91.97 3 2.825 d 5 86.37 102.47 87.56 106.56 94.94 1 1.169 d 6 110.41 127.01 102.56 151.91 115.69 3 7.851 d 7 102.69 102.35 75.88 110.25 100.62 3 24.943 d 8 86.00 88.38 67.59 102.77 80.20 3 18.00 d 9 101.47 98.56 90.67 107.03 97.01 3 6.554 d 1 93.14 74.80 80.67 81.62 73.86 5 0.939 d 9 101.47 98.56 90.67 107.03 97.01 3 6.554 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.01 88.59 105.61 66.61 90.99 4 1.985 d 1 95.95 56.70 74.12 50.75 57.56 4 5.949 d 1 195.96 177.09 c02.19 164.77 161.74 5 3.051 d 1 84.56 168.29 189.71 150.70 160.71 4 3.155 d 1 84.18 139.98 168.06 129.30 138.99 4 9.613 d 1 84.18 139.98 168.06 129.30 138.99 4 9.613 d 1 84.55 45.78 52.73 59.88 45.50 4 5.417 d 1 95.55 56.70 74.12 50.75 57.56 4 5.949 d 1 1 95.56 168.29 189.71 150.70 160.71 4 15.935 d 1 1 195.40 110.40 114.05 114.36 116.25 100.31 5 7.768 d 1 1 90.56 10.69 39 190.67 50.20 100.01 103.14 4 3.155 d 1 1 190.65 109.39 190.46 152.40 110.07 3 4 8.97 d 1 1 190.65 109.39 190.46 152.40 110.07 3 4 8.97 d 1 1 190.65 109.39 190.46 150.20 100.01 5 5.53 d 1 1 109.56 110.49 98.80 100.07 99.09 3 0.204 d 1 1 190.65 109.39 190.46 150.40 100.07 3 4 8.97 d 1 1 190.40 114.05 114.36 116.25 100.31 5 7.768 d 1 109.56	1	٨	84.15	108.29					
1 10 75.77 81.68 A5.00 95.30 76.02 1 1.053 2 1 60.60 49.86 59.52 02.75 51.48 2 1.626 2 2 135.29 103.77 139.07 97.36 95.46 3 155.18 129.81 150.34 133.40 129.00 5 0.804 2 4 115.78 81.40 97.59 86.68 84.79 2 3.390 2 5 44.25 55.83 50.22 54.08 35.88 5 0.193 2 6 70.54 61.11 59.78 74.43 61.16 5 1.531 3 1 101.16 09.72 A5.78 90.29 90.16 5 3.959 5 2 163.45 151.92 145.61 175.02 163.61 5 16.107 5 3 70.09 66.39 56.46 81.74 67.76 3 9.30 5 4 101.92 95.51 A9.14 108.95 91.97 3 2.825 5 A6.37 102.47 A7.56 106.56 94.94 1 1.169 5 A6.37 102.47 A7.56 106.56 94.94 1 1.169 5 A6.37 102.36 75.68 110.25 100.62 3 24.945 5 A8.67 102.36 75.68 110.25 100.62 3 24.945 5 A8.67 102.47 A7.56 106.56 94.94 1 1.169 5 A7.02.69 102.36 75.68 110.25 100.62 3 24.945 5 A8.67 102.47 A7.56 106.56 94.94 1 1.169 6 100.47 127.01 102.56 131.91 115.69 3 7.851 6 10.47 127.04 102.56 131.91 115.69 3 7.851 6 10.47 128.05 105.61 06.61 90.99 4 122.53 6 10 77.20 77.48 54.66 08.81 77.24 3 22.538 6 10 77.20 77.48 54.66 08.81 77.24 3 22.538 6 10 47.20 77.48 54.66 08.81 77.24 3 22.538 6 10 47.55 56.70 74.12 50.75 57.58 4 5.949 6 10 143 129.95 168.06 129.36 130.09 4 9.613 6 144.13 139.96 168.06 129.36 130.09 4 9.613 6 198.96 177.09 202.19 164.77 161.74 5 3.051 6 144.13 139.96 168.06 129.36 130.09 4 7.395 6 198.96 177.09 202.19 164.77 161.74 5 3.051 6 144.13 139.96 168.06 129.36 130.09 4 5.417 6 144.13 139.96 168.06 129.36 130.09 4 7.395 6 10 145.26 168.29 189.71 150.70 160.71 4 7.395 6 11 199.40 114.08 114.38 116.25 100.31 5 7.768 7 103.56 110.45 98.88 104.07 99.09 3 0.204 7 54.55 45.78 52.73 59.86 45.50 30.16 5 1.909 7 7 109.56 150.45 98.88 104.07 99.09 3 0.204 7 3 59.56 100.45 98.88 104.07 99.09 3 0.204 7 3 59.56 100.45 98.88 104.07 99.09 3 0.204 7 59.56 100.45 98.88 104.07 99.09 3 0.204 7 59.56 100.45 98.88 104.07 99.09 5 0.204 7 59.56 100.45 100.45 98.88 104.07 99.09 3 0.204 7 59.56 100.45 100.45 98.88 104.07 99.09 3 0.204 7 59.56 100.45 100.45 98.88 104.07 99.09 3 0.204 7 59.56 100.45 100.45 98.88 104.07 99.09 3 0.204 7 59.56 100.45 100.45 98.88 104.07 99.09 3 0.204 7 59	1	ú	37.29	56.38				1	
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2	5	5		103.77	139.07			5	1.901
2		3	155.18	129.81	150.34	133.40	129.00	5	0.804
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5					56.46	81.74	67.76	3	9.930
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3 10 77.20 77.48 54.66 88.81 77.24 3 22.538 4 1 93.14 74.80 80.67 81.62 73.86 5 0.939 4 2 95.01 88.59 105.61 66.61 90.99 4 1.985 4 3 131.47 106.22 122.52 100.00 103.14 4 3.155 4 4 75.55 56.70 74.12 50.75 57.56 4 5.949 4 5 198.96 177.09 202.19 164.77 161.74 5 3.051 4 6 184.18 139.98 168.06 129.38 130.99 4 9.613 4 7 54.55 45.78 52.73 59.88 45.50 4 5.417 4 8 99.33 78.05 85.57 64.22 76.72 5 1.528 4 90.35 78.05 86.43						102.77	8p.20		18.604
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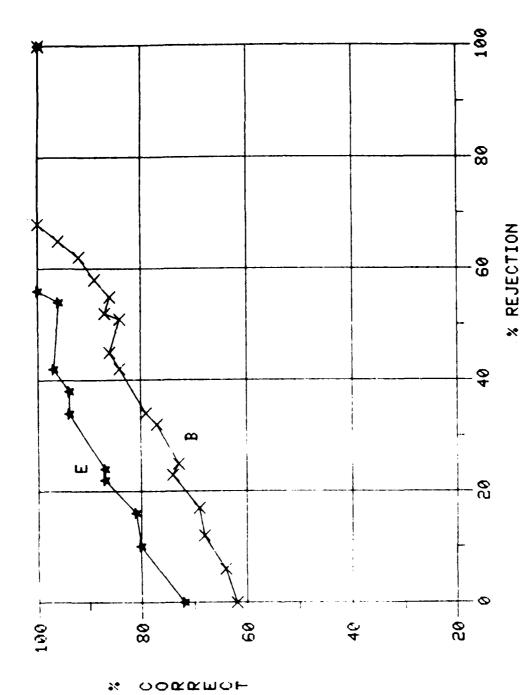


Figure 6 Performance Curve, Five-Language Experiment

SECTION VI DATA PROCESSOR SIMULATION

A. Overview

This section describes a computer simulation of a practical data processing system. The input to the real-time system is an audio signal that may or may not contain speech. It is assumed that the user is interested in only certain segments of speech data. The purpose of the system is to monitor the incoming signal and automatically detect and signal the occurrence of speech segments of interest. As implemented, the simulation accomplishes the following:

- (1) Stores all incoming data in digitized form on a random access disk;
- (2) Provides aural playout of the incoming data at the direction of an operator;
- (3) Detects the onset of speech in the data, marks the time of occurrence of this onset, and informs the operator of such;
- (4) Detects changes in the particular person producing speech when such changes take place, marks the time of occurrence, and informs the operator of such changes;
- (5) Detects the cessation of speech in the data, marks the times of occurrence of this cessation, and informs the operator of such;
- (6) Allows manual marking of the data by the operator at any desired time;
- (7) Allows aural prayout of the data commencing at any of the above marked occurrence times, at the discretion of the operator; and
- (8) Provides hard copy (line printer) documentation of the times of the above events, in chronological order.

In practice, such a system could greatly reduce the amount of human listening required to assure that speech segments of interest are detected. Also, the data storage requirement could be reduced by storing only those speech segments that are of particular interest.

B. System Operation

Input to the system is taken from an analog communication line. The input signal is low-pass filtered at the Nyquist rate, digitized at a sampling rate of 9.09 Hz, and immediately stored on a bulk storage device (random access disk). Unless directed differently by the operator, the system provides aural playout of the incoming data stream in real time. The operator controls the system by means of a set of key commands to a CRT/Keyboard terminal. The available commands are:

- S (Start) Begin monitoring and processing input data.
- P (Playout) Begin aural playout of data starting at commencement time of selected event.
- L (Listen) Resume playout of incoming data.
- M (Mark) Mark data at current time, assign an event number.
- Q (Quiet) Cease aural playout.
- E (End) Suspend monitoring of input data.
- T (Terminate) End all processing.

Upon receiving the S command, the system initiates data processing. All incoming data are stored on disk and processed to automatically detect onset and cessation of speech, and speaker changes. Storage and processing continue without interruption until the command E is received. When such a speech event is detected, an event number is assigned; then the event number, the associated occurrence time, and an event description are printed by the line printer and are displayed on the operator's terminal.

The commands P, L, M, and Q are given by the operator at times of his discretion. The line printer records the occurrence times and descriptions of all such commands in the time sequence that they are given. These commands are executed immediately upon occurrence and do not affect the internal storage and event detection system functions. The P command causes interrogation of the operator as to which event he would like to hear. Aural playout commences at the occurrence time of the event indicated by the operator. Playout continues until the next operator command.

C. Event Detection

The automatic detection of speech-related events accomplished by this system is based on the estimated pitch track computed according to the modified cepstral pitch tracking algorithm of Markel.⁶ For each 25 ms frame of data, a voiced-unvoiced decision is made. If the decision is voiced, an estimate is made of the pitch for that frame. Such pitch estimates are in the range [40,230] Hz. If a frame is deemed to be unvoiced, the value 0 is assigned for the pitch track value for that frame.

A "smooth pitch" function, Ps, is defined for each frame of data to be the number of frames, in the preceding two seconds of data, for which the pitch in a given frame differs from the the pitch for the immediately preceding frame by less than 10%. When the function Ps becomes greater than 15 (approximately 20% of the number of frames in the window) a tentative decision is made that speech is present in the incoming data. However, a firm decision is delayed to check for certain non-speech sounds that remain voiced longer than 1.5 seconds. (Speech segments are rarely voiced longer than 0.75 second.) Thus, if the threshold 15 has been reached by Ps, and no voiced segment is longer than 1.5 seconds, the onset of speech is signalled by the system. When speech is being detected and the function Ps decreases to less than 8, cessation of speech is signalled to have occurred. This procedure rejects signals for which the pitch fluctuates too rapidly to be speech and signals that remain "voiced" too long to be speech.

To signal a change in speakers, a smoothed version of the function Ps is used. This new function, Pm, is a three-second moving average of the function Ps. Let Pm(k) denote the value of this function at the end of the k-th voiced segment, where the end of the voiced segment is determined as in the preceding paragraph. If Pm(k) differs from Pm(k-1) by more than 10%, then the system signals a possible change in speakers.

This system, used in on-line, informal tests with microphone input, performed quite well, rejecting non-speech sounds that included whistles, laughter, and various types of music. All speaker changes were detected.

D. System Extensions

A data processing system as described in this section could be extended in several directions to provide additional time- and labor-saving features. Automatic language discrimination could be incorporated to provide high-level elimination of speech data that is of no interest. Speaker authentication could be used in instances where only data from a specific person, whose identity is known, is of interest. Key-word detection could be used to flag only that speech relevant to certain prespecified subjects of interest.

SECTION VII

The RADC language classification data base was expanded from five languages to seven languages with the addition of 31 sessions of data from 17 speakers of L7 and 33 sessions of data from 14 speakers of L8.

An interactive reference sound specification procedure was devised that allows great flexibility in defining references. This procedure allows selection based on factors relating directly to language specificity, rather than imposing restrictions as to length or format of the resulting pattern. Collections of 54 reference sounds from the original five languages and of 80 references from all seven languages were specified using this procedure and were used as language discrimination reference files.

Data from a set of design speakers were used to estimate language likelihoods for each of the reference sounds. These likelihoods are parameters of the summed log-likelihood decision rule used to test language discrimination performance using a separate set of speakers, of approximately the same size. A rejection strategy was incorporated that allowed disregarding speakers for whom a decision is not clear-cut.

Application of the 54 element, five-language reference file and the above test procedure in a five-language experiment yielded 100% correct classification with a reject rate of 56% (of 50 test speakers). In a test involving the set of 80 references from seven languages, 100% correct classification was obtained with 68% rejection of the 65 test speakers. These results indicate that a practical data processor can be devised that can automatically classify more than 30% of the incoming data with essentially no error and inform an operator exactly which data must be manually processed.

A data processor simulation was implemented that demonstrated automatic data processing in action. This simulation included automatic detection of onset and cessation of speech and changes in the particular speaker, along with concurrent aural playout of either the incoming data or operator-selected prestored data.

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